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Effect of Strain Rates and Pre-Twist on Tensile Strength of Kevlar KM2 Single Fiber

by Brett D. Sanborn and Tusit T. Weerasooriya

ARL-TR-6403 **April 2013**

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Brett D. Sanborn

Oak Ridge Institute for Science and Education

Tusit T. Weerasooriya

Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

High-performance fibers such as Kevlar (Kevlar is a registered trademark of DuPont Company) KM2 used in protective vests are loaded primarily in tension at high-loading rates during impact. During the weaving and crimping process of fibers/yarns to make fabrics, individual fiber tensile strength may become reduced due to pre-straining of fibers by twisting. To systematically investigate the effect of loading rate on the fiber strength under different pre-twisted stress states, a miniaturized Kolsky tension bar is used to study single Kevlar KM2 fibers subject to varying levels of preset shear strain at high- ($1200\ \mathrm{s^{-1}}$) strain rates. Low- ($0.001\ \mathrm{s^{-1}}$) and intermediate- ($1\ \mathrm{s^{-1}}$) strain rate responses of the fibers are investigated using a Bose Electroforce loading system. In this report, tensile strength is presented as a function of preloaded shear strain on a single fiber for different strain rates of loading. The fiber behaved similarly at all investigated strain rates. Below the threshold shear strain of ~0.15, the fiber retained 95% of the original untwisted virgin strength. Fracture morphology of the fibers is also investigated using a high-resolution scanning electron microscope to understand the mechanisms of failure.

15. SUBJECT TERMS

SHPB, Kevlar KM2, single fiber, tensile strength degradation, high rate, effect of pre-shear strain, stress-strain, loading rate, effect of twist

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1. Introduction

Woven fabrics have been employed in a wide range of applications in both consumer and defense products. Improving effectiveness of woven products in military and defense applications requires development of predictive models using finite element codes. To develop predictive capabilities for multiscale hierarchically organized fiber based systems such as fabrics, multifabrics, and fabric-based polymer resin composites based on the response of smaller length scale requires knowing the mechanical response of single filaments. With such a multiscale predictive capability, measurement of the response of the smallest unit is required, allowing optimization of a variety of larger scale systems based on single fiber response. Fabric-based devices are used to protect under impact and blast loading conditions. These devices and their constituents such as fibers are subjected to different rates of loading, especially high-loading rates. A typical yarn of Kevlar* fiber is composed of a few hundred to a few thousand single filaments. During production, weaving, or in general use, it is plausible that single filaments may become twisted and loaded to some amount of shear strain. Determining how preloaded shear strain affects the tensile properties of the single fiber under a variety of loading rates provides an insight to how the fibers degrade due to twisting, as well as provide a quantifiable measure of fiber damage to be used in computer simulation of the impact on the larger scale fabric-based systems.

Prior to the investigation by Cheng et al. (*1*) in 2005 there were no investigations of single fiber longitudinal tensile response at high-loading rate. Cheng et al. (*1*) developed a specialized tensile split-Hopkinson Tension bar (SHTB) to obtain the tensile response of microscale single fiber (fiber-SHTB) and found that the tensile stress-strain response was linear and elastic until failure. Furthermore, insignificant loading rate effects on tensile strength of Kevlar KM2 were found when the loading rate was varied from quasi-static (0.00127 s^{-1}) to high rate (2500 s^{-1}); a strength of 3.88 ± 0.40 GPa was found for the fiber at quasi-static rate, while at high rate the ultimate strength was 4.04 ± 0.38 GPa. Cheng et al. (*1*) also investigated the longitudinal Young's Modulus and Poisson's ratio v_{31} of the fiber. In a subsequent publication, Cheng et al. (*2*) also developed another new experimental technique to explore the transverse mechanical properties of the fiber, and investigated the residual tensile strength of the fiber following transverse mechanical loading. This transverse experimental method is a variation of the technique developed by Singletary et al. (*3*). The transverse elastic modulus of KM2 was found to be significantly lower than the longitudinal modulus.

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*Kevlar is a registered trademark of DuPont Company.

Lim et al. (*4*) examined the longitudinal tensile behavior of single A265 fiber at both quasi-static and high-strain rates using the same experimental methods by Cheng et al (*1*). Using the experimental method by Cheng et al. (*2*), Lim et al. (*4*) investigated the transverse mechanical response of A265 in addition to loading rate effects on longitudinal tensile strength. Lim et al. (*4*) completed a systematic study of the effect of gage length of the fiber sample to gain an insight into a possible defect distribution at the single fiber level along the fiber. Lim et al. (*5*) improved the fiber-SHTB experimental setup presented by Cheng et al. (*1*) through the use of a laser extensometer to more accurately measure strain due to the small displacement of the tension bar. Lim et al. (*5*) investigated the loading rate and gage length dependence on tensile strength of Kevlar 129. Additionally, the compliance correction method for low-rate fiber experiments presented in ASTM 1557-03 was applied to the dynamic experiment (*5*). Lim et al. (*6*) completed an experimental investigation of gage length and strain rate effects on three different fibers including an unspecified type of Kevlar, referred to as "Kevlar" in the paper, Kevlar 129, and Twaron. In addition to studying rate effects on strength, tensile experiments on fibers taken from protective vests over a 10-year period stored at laboratory conditions were investigated; only small changes in the ultimate strengths of the fibers over the 10-year span were found.

DeTeresa et al. (*7*) studied the anisotropy of single Kevlar 49 fibers. Experimental investigations included tensile behavior at low rate, transverse compression of a single fiber embedded in a matrix, measurement of the recoverable strain after twisting, and tensile strength of longitudinally twisted fibers at low rate. Tensile experiments on twisted fiber were accomplished by attaching a fiber to a disc pendulum, twisting the pendulum to a desired shear strain, and loading by a low-rate Instron machine to failure. DeTeresa et al. (*7*) found that in general, a loss in tensile strength occurred after application of more than 0.10-shear strain; no increase in strength was seen as a function of twist at low rates. Similar to the work on Kevlar by DeTeresa et al. and Hudspeth et al. (*7, 8*) studied the properties of Dyneema fiber under a pre-twisted stress state. Dyneema fibers subjected to varying levels of pre-twist were pulled in tension under high-strain rate and the tensile stress history was recorded. The value of shear stress induced by pre-twisting in the fiber was estimated from separate experiments using a torsional pendulum. The shear stress was calculated using the angular velocity of the pendulum, which was related to the torque on the fiber. The quasi-static induced shear stress was related to the high-rate tensile stress for Dyneema fiber.

Experimental studies on twisted yarns have been conducted by a few researchers. Wilfong and Zimmerman (*9*) first studied the effect of pre-twist on tensile strength of Kevlar yarn. Wilfong and Zimmerman defined a "twist multiplier," (TM) based on the denier and twist of the fiber and found an optimal value of 1.1, which gave a maximum strength compared to other amounts of twist at the same denier. Similar studies were completed on Kevlar KM2 yarns at the U.S. Army Research Laboratory (ARL) by Mulkern and Raftenberg (*10*). Using a different type and denier of Kevlar than Wilfong and Zimmerman, Mulkern and Raftenberg found an optimal TM of 1.2, which is close to the value found by Wilfong and Zimmerman (*9*). The authors of the studies

posit that the increase in strength with twist is due to the frictional effects between single fibers within the yarn; when the filament within a twisted yarn breaks, although it cannot support load at the breaking point, the filament can support load remote from the breaking point due to frictional contact between neighboring yarns (*9*, *11*).

While investigations of low- and intermediate-rate properties of Kevlar are useful for material modeling applications, high-rate material properties are more applicable since fibers are loaded at high rates during ballistic use. The purpose of this study is to systematically investigate the high-rate properties of single Kevlar fibers under the pre-twisted stress state. Similar to the study by DeTeresa et al. (*7*), tensile behavior of twisted fibers is investigated at low rate (0.001 s^{-1}), and is extended to intermediate (1 s^{-1}), and high rate ($\sim 1200 \text{ s}^{-1}$) to understand the loading rate effects on the tensile behavior as a function of pre-twist on the single Kevlar KM2 fibers taken from a 600 denier yarn.

2. Experiments

2.1 Materials and Test Program

To study the effect of pre-twisting on the tensile strength of Kevlar KM2 fiber, single fibers were extracted from KM2 600 denier Kevlar yarns. A 30-cm long single fiber was extracted from a yarn and was used to make ~13 individual samples. A 2.6 cm-section of fiber was taken from the end and used for the scanning electron microscope (SEM) measurements. SEM micrographs were taken at three points along each 2.6-cm section of fiber. Five measurements were taken for each micrograph. The 15 measurements were averaged and were used as the representative diameter of each of the 13 fiber specimens made from that fiber. The average diameter of the fibers used in this study was $12.67 \pm 0.66\ \mu\text{m}$. Single fibers were mounted and glued on cardboard tabs at a standard gage length of 5.2 mm for testing using 3M DP8005 epoxy. The cardboard tabs were glued to stainless steel setscrews so that specimens could be easily swapped out from the testing apparatus. A photograph of a completed specimen is shown in figure 1. The diamond-shaped cutout in the center of the cardboard tab aids in axial alignment of the fiber. The setscrews were glued to the cardboard using an alignment fixture to ensure no off-center loading occurred.

To investigate a wide range of shear strains similar to DeTeresa et al. (*7*), a total of 10 levels of shear strain were selected for quasi-static, intermediate, and high rate. At each strain rate, nine single fibers were used. At each shear strain level, a fiber sample was tested from each of the nine fibers for a total of 270 individual experiments in the study. The strength of the nine fibers for each shear strain at each strain rate was averaged. Table 1 lists the investigated shear strain levels for each of the three different strain rates in this study. The approximate number of 360°

rotations is also shown; the exact twist angle was different for each fiber due to variations in diameter. The fibers were assumed to be untwisted when glued to the cardboard tabs. It is possible that a fiber was twisted during mounting; however, any twisting was most likely less than a 360° rotation, which over a 30 cm length of fiber represents a shear strain of <0.0003, which is negligible compared to the shear strains studied.
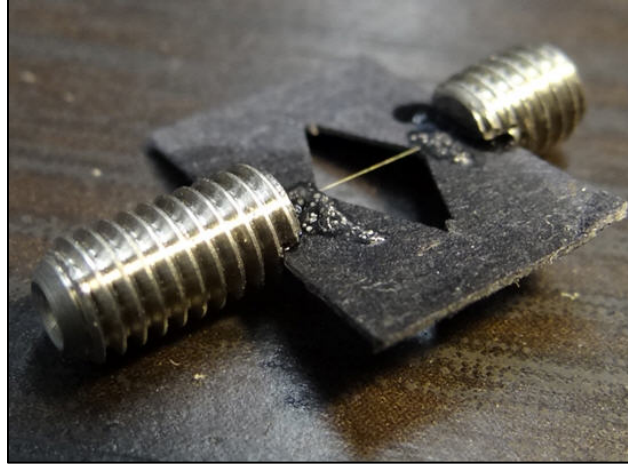

Figure 1. Typical high-rate specimen. Low-rate
specimens used only one setscrew for mounting.

Table 1. Shear strain levels
examined in this study.

Shear Strain	Approximate No. of 360° Rotations
0	0
0.005	<1
0.02	3
0.05	7
0.08	11
0.10	13
0.15	20
0.25	33
0.35	48
0.45	60

To determine the shear strain in the fiber, the fiber was assumed to be thin rod. The shear strain, γ, was calculated as

$$\gamma = \frac{\theta d}{2L},$$

(1)

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where θ is the deflection angle, d the fiber diameter measured in the SEM, and L the length of the fiber. The distribution of shear strain in this case is taken to be highest at the surface of the fiber.

2.2 Quasi-Static and Intermediate Rate

Quasi-static and intermediate rate experiments were completed at rates of 0.001 s^{-1} and 1 s^{-1} on a Bose Electroforce test bench. For quasi-static and intermediate rate testing, one setscrew was mounted on the end of a cardboard frame with the mounted fiber. The single setscrew was inserted into a rotary stage and clamped on the other end using a grip, as shown in figure 2. Prior to testing, the sides of the cardboard tab were cut away allowing the single fiber to span between the grips; care was taken to ensure that the delicate single fiber was not prestressed. After clipping the sides of the support tab, the fiber was slackened and the rotary stage was spun to the desired level of shear strain, and the experiment was carried out. This differs from the method used by DeTeresa et al. (*7*). DeTeresa et al. attached the fiber to a cardboard tab and then to a disk. The sides of the tab were removed and the disk was rotated until the desired level of shear strain was reached, indicating that the fibers were under tensile load while the shear strain was introduced. The gage length used by DeTeresa et al. was also considerably longer at 200 mm compared to the 5.2-mm gage length used in this study.
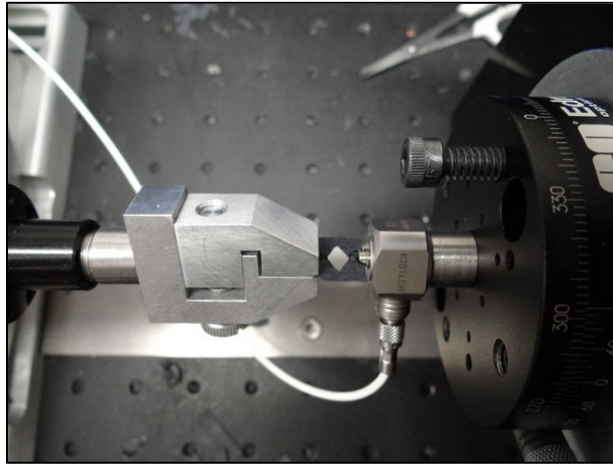
Figure 2. Setup for low- and intermediate-rate experiments.

2.3 High Rate

In order to investigate loading rate effects over a wide range at the pre-twisted stress state, a mini SHTB was used. The SHTB has been extensively used to investigate rate effects in a variety of materials; furthermore, the mini SHTB has been widely employed in recent years to study axial response of single fibers (*1*, *2*, *4–6*). In the dynamic experimental setup used in this study, a tubular striker is fired by a gas gun and impacts a flange to generate an incident tensile stress pulse that travels down the bar to the specimen end. A photograph of the setup is shown in

figure 3, while a schematic is shown in figure 4. This method is the same as a conventional SHTB, though traditionally in a fiber experimental setup, springs have been used to propel the tubular striker toward the flange (*1*, *2*, *4–6*); however, in this case a gas-driven firing system was used. The incident bar is a 6.35-mm diameter 7075-T6 aluminum bar and 1828 mm in length. The tubular brass striker used was 355 mm in length, 10 mm in diameter, with a wall thickness of 0.36 mm. A pulse shaper made of copper tape was used to generate a smooth loading pulse and eliminate high-frequency oscillations. Semiconductor strain gages mounted on the incident bar were used to collect the strain history in the bar.
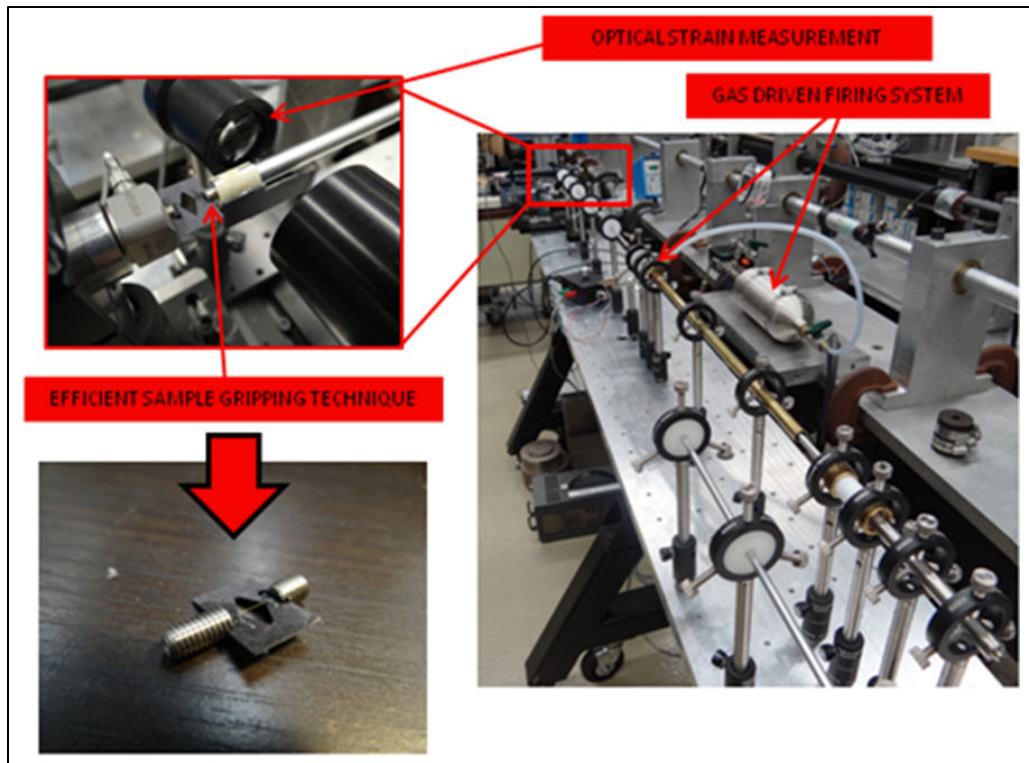
Figure 3. Photo of fiber-SHTB.
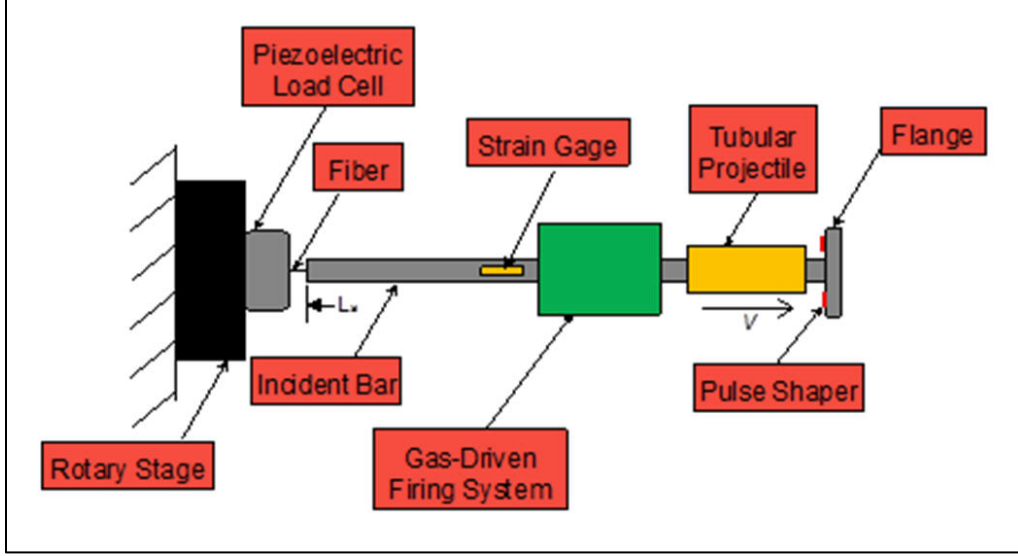
Figure 4. Schematic of fiber-SHTB.

The strain rate of the specimen is calculated using the equation (*12*):

$$\dot{\varepsilon} = -\frac{v}{l_s} = \frac{c_0}{l_s}(\varepsilon_i - \varepsilon_r),$$

(2)

where v is the particle velocity at the end of the bar, l_s is the length of the sample, and c_0 is the wave speed in the bar. ε_i and ε_r are the incident and reflected pulses, respectively. The stress history of the sample is calculated using

$$\sigma = \frac{F}{A},$$

(3)

where F is the load recorded by the load cell, and A is the cross-sectional area of the fiber.

The specimens used in the high-rate experiments were identical to the quasi-static and intermediate-rate experiments, except two setscrews were glued to the sample tabs, which allowed one end to be threaded into a quartz-based Kistler load cell (9712B5), while the other end was threaded into an adapter on the end of the incident bar. The sides of the fiber tab were cut so that the fiber spanned between the load cell and bar end. A small amount of slack was introduced into the fiber and the rotary stage rotated to a desired level of shear strain. The sensitive piezoelectric quartz-based load cell was used because the force transmitted by the single fiber is low, about 0.05–0.5 N, depending on the amount of pre-twist. After each experiment, the fiber tabs were inspected optically using 10× magnification to verify that the fiber broke within the gage section.

3. Results and Discussion

The output signal of a typical high-rate experiment is shown in figure 5. The strain and force signals were recorded by semiconductor gages mounted on the incident bar and the fixed piezoelectric load cell on the output side. Figure 6 shows the strain rate and stress histories from this experiment. Figure 6 shows that after a rise time of about 60 µs the strain rate reached a constant value of 1150–1200 s^{-1} for 35 µs until failure. The positive force slope curve over the duration of the test shows that the fiber did not pull out of the glue. If pullout were evident, the force would rise followed by a flat portion where the fiber takes a small amount of load until the fiber comes back into contact with the glue followed by another rise and so on until failure.
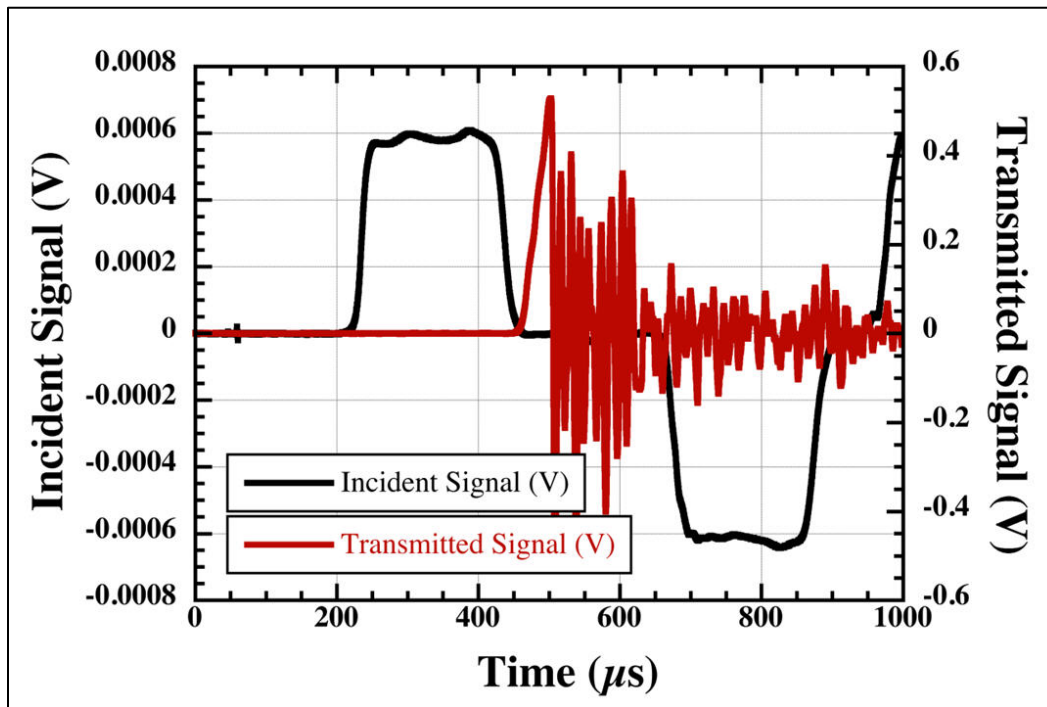
Figure 5. Raw data from a high-rate experiment.
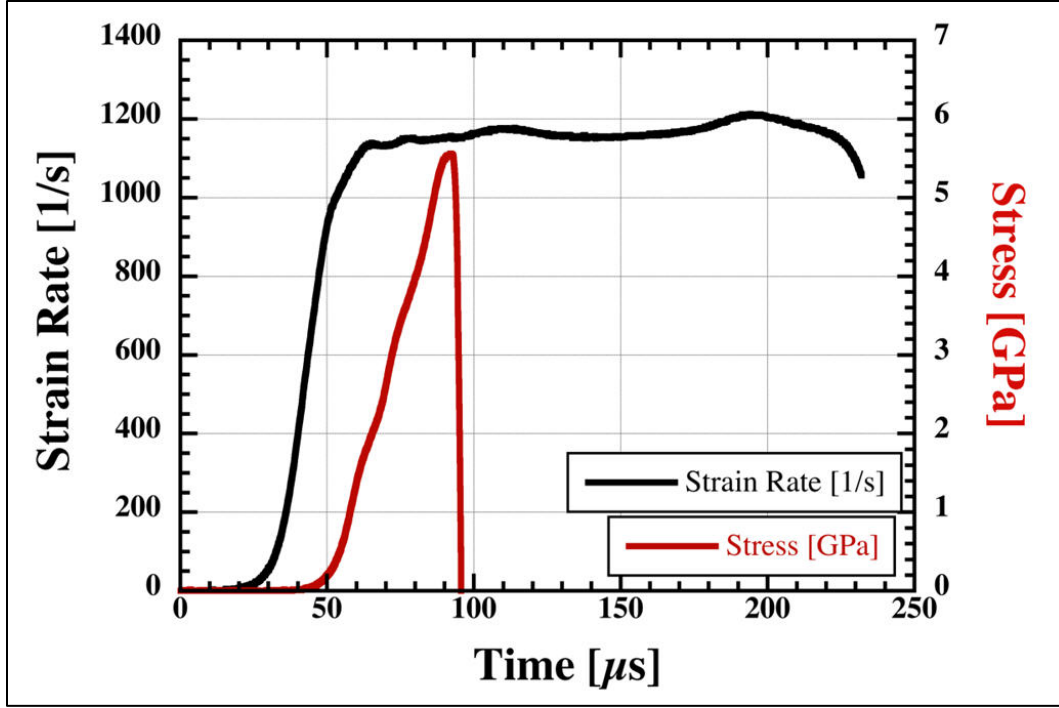
Figure 6. Strain rate and stress histories from a high-rate experiment on a single Kevlar KM2 fiber.

Results from twist experiments on low, intermediate, and high rates are shown in figure 7, and a full table of the individual data points with standard deviations from each group of data points is shown in table 2. The results at each strain rate have been normalized to the ultimate strength of the untwisted fiber at each respective rate in figure 7. The baseline value for the ultimate strength of the fiber at low rate was 4.51 ± 0.21 GPa. Pulling twisted fibers at low rate revealed no increase in ultimate strength when the fiber was twisted. For low-rate experiments, as the shear strain increases up to about 0.15, the fiber retains at least 95% of the untwisted strength. After ~0.15-shear strain is reached, the strength retained by the fiber decreased. The results of DeTeresa et al. (7) are plotted alongside the results from this study in figure 7. DeTeresa's results show that the decrease in strength happens at around a shear strain of 0.10. One reason for the 5% difference in the drop-off in strength could be the fiber type; DeTeresa et al. (7) used Kevlar 49, whereas KM2 was the type of fiber used in this study.

Similar to the low-rate results, the tensile strength of the twisted fiber at intermediate rate retained at least 93%–95% of the untwisted strength up to a shear strain of ~0.15. The baseline value of ultimate strength for KM2 fibers tested at intermediate rate was 4.64 ± 0.31 GPa.

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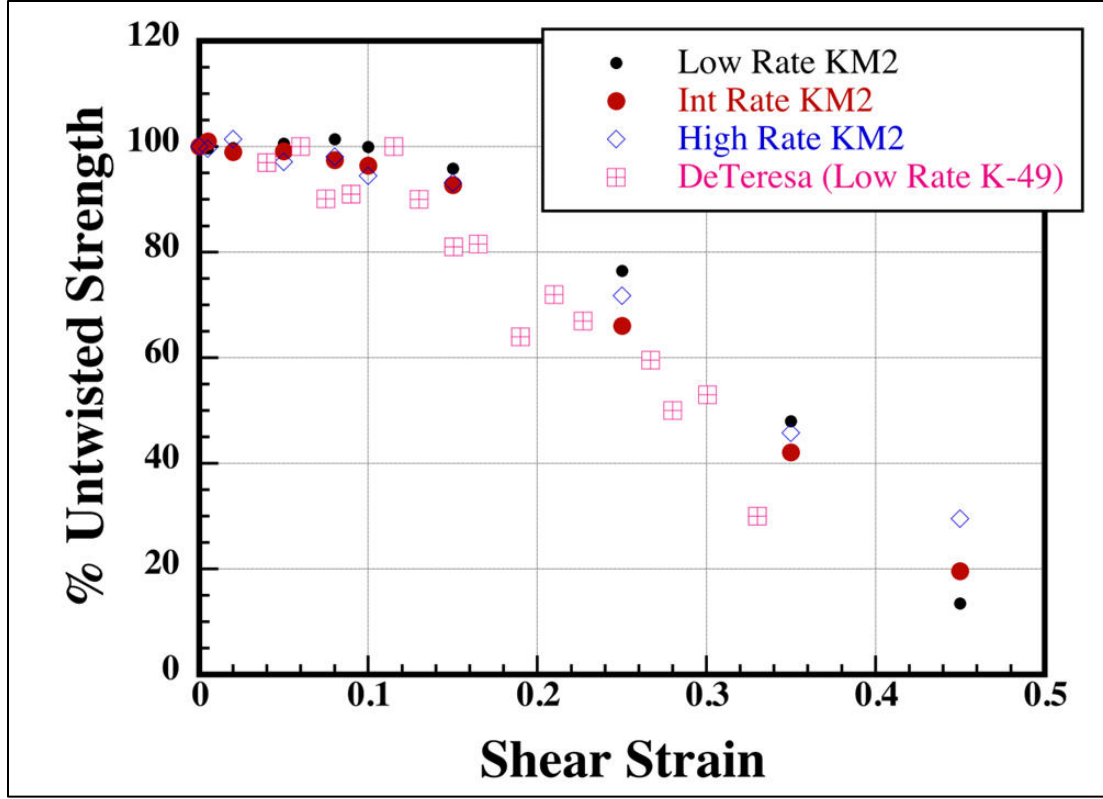
Figure 7. Results from twist experiments at various strain rates.

Table 2. Full results at each strain rate. Each value in the strength columns represents an average of nine experiments with the standard of deviation of each data set.

Shear Strain	Low Rate (0.001 s⁻¹)			Intermediate Rate (1 s⁻¹)			High Rate (~1200 s⁻¹)		
	Strength	Stdev.	(%)	Strength	Stdev.	(%)	Strength	Stdev.	(%)
	(GPa)	(±)	Untwisted	(GPa)	(±)	Untwisted	(GPa)	(±)	Untwisted
0	4.51	0.21	100.00	4.64	0.31	100.00	5.14	0.26	100.00
0.005	4.49	0.22	99.70	4.69	0.26	101.00	5.12	0.39	99.62
0.02	4.50	0.22	99.75	4.59	0.28	98.98	5.21	0.48	101.45
0.05	4.53	0.25	100.59	4.60	0.33	99.12	4.99	0.40	97.11
0.08	4.57	0.26	101.43	4.52	0.24	97.44	5.04	0.40	98.09
0.1	4.51	0.34	99.96	4.47	0.18	96.43	4.85	0.24	94.47
0.15	4.32	0.40	95.86	4.30	0.26	92.70	4.78	0.40	93.13
0.25	3.45	0.29	76.45	3.07	0.25	66.05	3.69	0.31	71.78
0.35	2.16	0.20	48.01	1.95	0.19	42.09	2.35	0.27	45.77
0.45	0.61	0.41	13.47	0.91	0.43	19.60	1.52	0.43	29.54

The effect of strain rate of the untwisted strength is shown in figure 8. The tensile strength of untwisted KM2 fiber under high-rate loading was 5.14 ± 0.26 GPa. This value is 1 GPa stronger than the value found by Cheng et al. (*1*) for KM2, but it is similar to the value found by Lim et al. (*5*) on previously woven fibers taken directly from protective vests, though the specific type of fiber from the vests was not specified in that study. The high-rate behavior of twisted fibers resembles the low- and intermediate-rate behavior. Up to a preset shear strain level of about ~0.15, the fiber retains about 93% of the untwisted strength. This indicates that Kevlar is not rate dependent with respect to preset levels of shear strain.
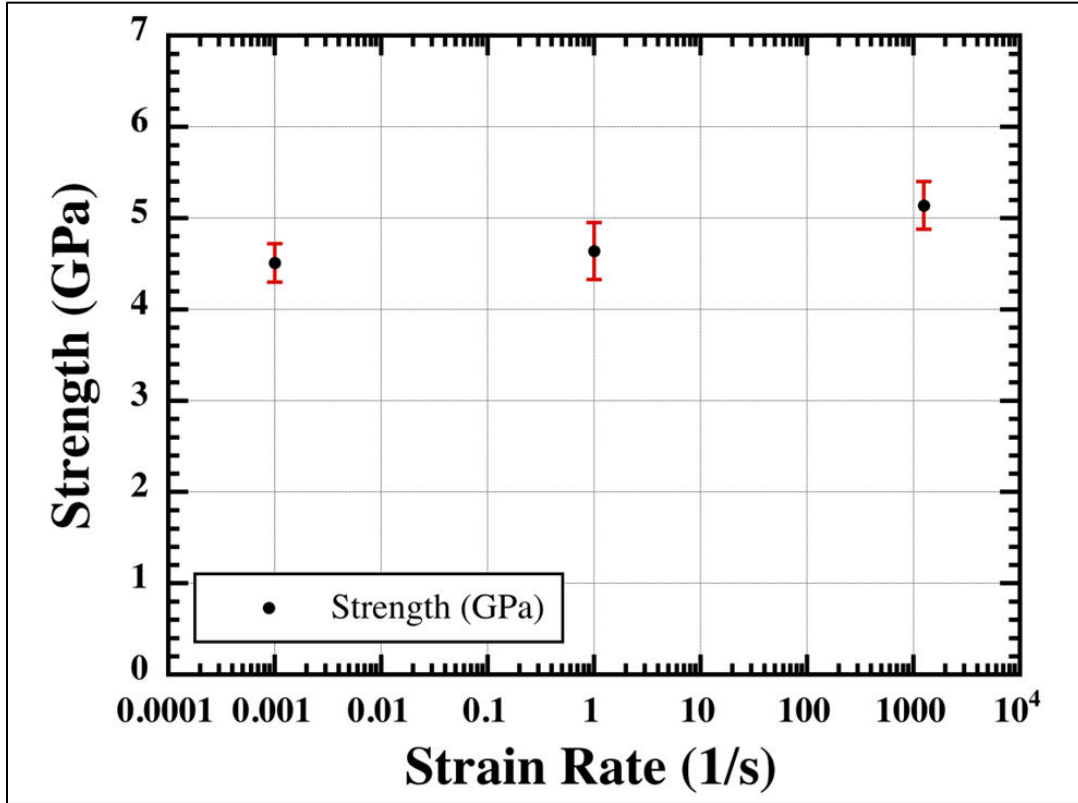
Figure 8. Strain rate effect of untwisted fiber.

The lack of an increase in fiber strength at all strain rates indicates that the increase in strength seen by Wilfong and Zimmerman (*9*) and Mulkern and Raftenberg (*10*) when twisting yarns is an effect of the single fiber interactions within the yarn such as load transfer via friction. If the increase in strength were a material property of individual Kevlar fibers, this study would have seen an increase at small shear strains. Furthermore, load transfer via friction analogous to Willfong and Zimmerman (*9*) must also not be occurring among the fibrils in the fiber, since no increase in strength was seen.

3.1 SEM Images

Fibers twisted to multiple levels of shear strain were imaged using SEM to see the surface morphology. Shear strains of 0 and 0.02 showed no signs of surface defects on the fiber as a result of twist as shown in figure 9. A shear strain of 0.08 began to show small signs of surface defects as a result of twist. At 0.15-shear strain, surface defects become visible. At 0.25- and 0.35-shear strain, the depth of the surface flaws introduced by twisting increases.
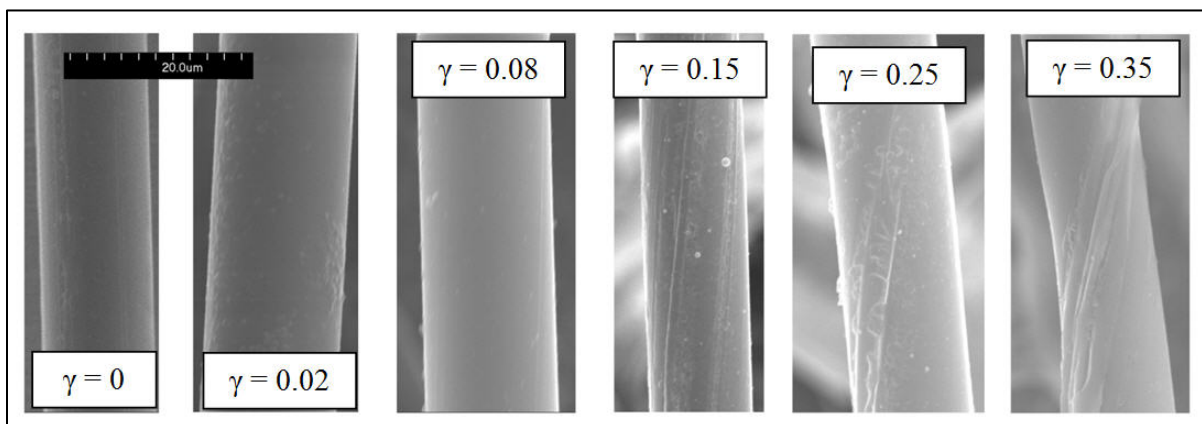
Figure 9. SEM micrographs of Kevlar fibers held at varying levels of shear strain. Note that the scale bars are only an approximate measure of length for each micrograph.

Random samples of the ends of the failed fibers were selected and inspected using an SEM. The common failure mode of the failed fibers at all loading rates was fibrillation, which is consistent with other work done on Kevlar fiber at a variety of loading rates (1, 2, 5, 6). In general, the ends of the failed fibers twisted to shear strain above 10% showed residual signs of the induced twist independent of loading rate. Fibers twisted to shear strains below 0.10 tended to have longer fibrillated ends with no signs of residual twist compared to those above 0.10, as shown in figure 9.

Figure 10a shows the failed end of a fiber twisted to 0.05-shear strain and tested at intermediate rate, whereas figure 10b shows a fiber twisted to 0.35 and pulled at the same rate. The 0.05 fiber shows no signs of residual twist near the point of failure. Helical splitting is depicted in figure 10b on the 0.35-shear strain fiber.

SEM images of fibers strained in shear to 0.45 seemed to have more localized failure compared to fibers pre-strained to lower levels. This localized failure behavior, shown in figure 11, could be the cause for the low strength of the fiber pre twisted to 0.45-shear strain compared to the untwisted fiber; the strength of the pre twisted fiber at 0.45 decreased to about 13%–30% of the untwisted fiber strength depending on the loading rate. However, the high-strain rate sample shown in figure 11 seems to have both localized failure at the end and longer fibrillated ends. A limited number of samples were imaged using SEM; imaging a larger set of failed fibers would give a better idea of the failure behavior of the twisted fibers.
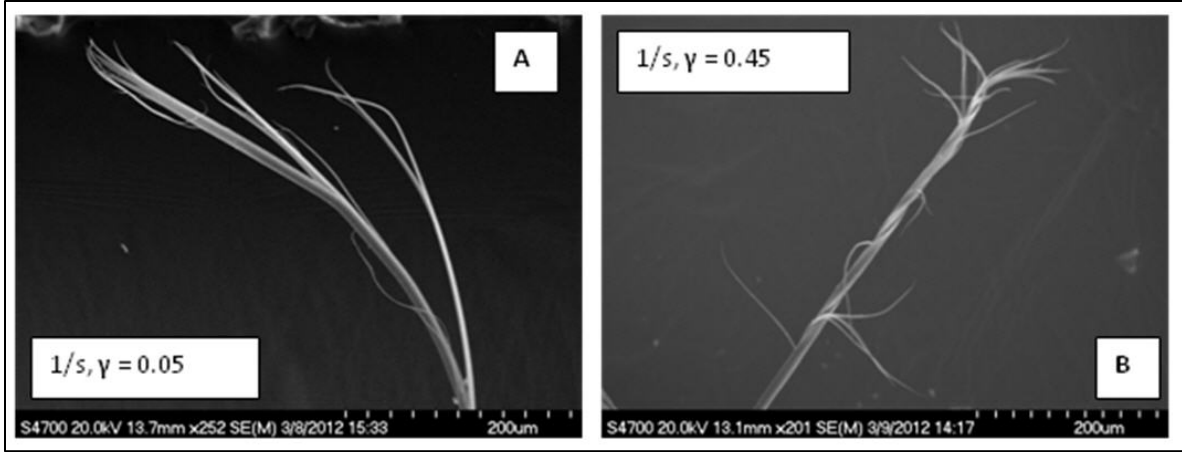
Figure 10. Failed ends of fiber samples tested at intermediate rate with pre-shear strains of 0.05 and 0.35.
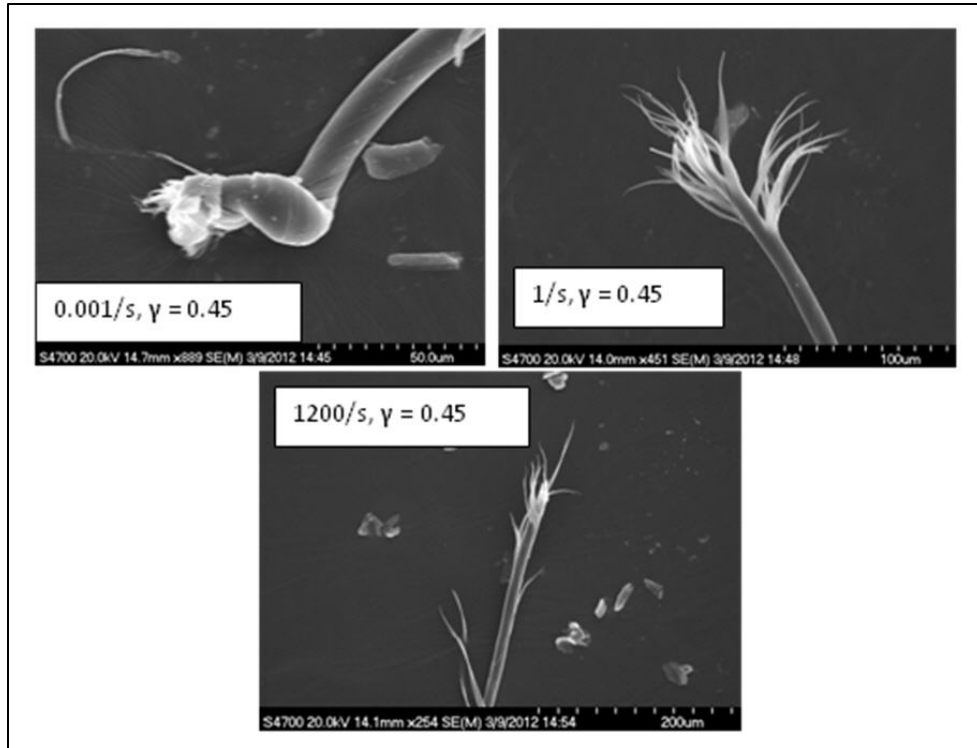
Figure 11. Localized failure behavior of fibers tested at three strain rates subject to 0.45-pre-twisted shear strain.

From the limited number of SEM images of the failed fiber ends, the fibers twisted to shear strains above 0.10 showed residual signs of twist after the test. Evidence of the residual twist in the fibers post test is shown in figure 10b follows the result of DeTeresa et al. (7) that the maximum amount of recoverable torsional strain is about 0.10. In other words, past 0.10 the fiber experienced permanent deformation. This permanent deformation behavior is shown in the imaging of the damaged fibers. Another possibility for this residual twist could be the recoil

behavior of the fiber after failure occurs. Each fiber sample seemed to recoil differently after completion of the experiment. Hence, imaging a greater number of failed fiber ends in the SEM is required to know the full failure behavior of the fiber.

4. Summary

Tensile experiments on pre-twisted Kevlar KM2 single fibers were conducted at low and intermediate rates of 0.001/s and 1/s, using a Bose Electroforce test bench and at high rate of ~1200/s using a fiber-SHTB. The ultimate strength of the pre-twisted fiber was not found to be dependent on the loading rate. Fibers pulled at low and intermediate rate decreased in strength below 95% of untwisted strength past shear strains of ~0.15. At high-loading rate, fibers behaved similarly; more than 93% of the untwisted strength was retained up to a shear strain level of ~0.15. Considering only ultimate strength, the untwisted fibers showed a small strain rate effect as seen by the increase in strength when the strain rate was varied from 0.001/s to 1200/s. SEM images of the damaged fiber showed fibrillated ends. The failed ends of fibers past 0.10–0.15-preset-shear strain showed signs of residual twist and permanent deformation in the fiber, whereas fibers twisted to shear strains of 0–0.10 did not. More localized failure of fibers twisted to 0.45-shear strain was found at all loading rates; however, a limited number of samples were imaged in the SEM—more samples are needed to fully describe the failure behavior. The retention in strength up to 0.15-shear strain is encouraging from a composites processing standpoint—as long as individual fibers are not twisted during the crimping process and weaving past 0.15-shear strain, protective equipment should function with 95% effectiveness based only on these single fiber tension results. Analogous behavior seen in twisted yarns was not found in the single fiber results indicating that the increase in tensile strength in twisted yarns must be an effect of the single fiber interaction instead of occurring inside the individual fibers.

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